Neutrino Flavor Ratio on Earth and at Astrophysical Sources

Kwang-Chang Lai,[1,2] Guey-Lin Lin,[1,2] and T.C Liu[1,2]

[1]Institute of Physics, National Chiao-Tung University, Hsinchu 300, Taiwan
[2]Leung Center for Cosmology and Particle Astrophysics,
National Taiwan University, Taipei 106, Taiwan.

April 8, 2010

Abstract

We present the reconstruction of neutrino flavor ratios at astrophysical sources. For distinguishing the pion source and the muon-damped source to the 3σ level, the neutrino flux ratios, $R \equiv \phi(\nu_\mu)/(\phi(\nu_e) + \phi(\nu_\tau))$ and $S \equiv \phi(\nu_e)/\phi(\nu_\tau)$, need to be measured in accuracies better than 10%.

1 Introduction

Astrophysical neutrino sources are characterized by their neutrino flavor ratios. For example, the pion source generates the neutrino flavor ratio, $\{\phi(\nu_e) : \phi(\nu_\mu) : \phi(\nu_\tau)\} = \{1 : 2 : 0\}$, where neutrinos are produced by pion decays and the subsequent decays of muons. In the muon-damped source, the neutrino flux produced by muon decays are suppressed due to interactions of muons with strong field or matter [1, 2, 3], and the flavor ratio of muon-damped source is $\{\phi(\nu_e) : \phi(\nu_\mu) : \phi(\nu_\tau)\} = \{0 : 1 : 0\}$. Due to the neutrino oscillation effect, the flavor ratio observed on Earth is different from that at the astrophysical source. It is possible that two rather different sources may generate almost the same flavor ratio on Earth after neutrino oscillations. Neutrino telescope measures the flux-ratio parameters $R \equiv \phi(\nu_\mu)/(\phi(\nu_e) + \phi(\nu_\tau))$ and $S \equiv \phi(\nu_e)/\phi(\nu_\tau)$. In this talk, we discuss the discrimination of astrophysical neutrino sources, taking into account the uncertainties on neutrino mixing angles, CP violation phase and achievable accuracies for determining R and S.

2 Statistical Analysis

The initial neutrino flux and the observed neutrino flux on the Earth is connected by the probability matrix P via

$$\begin{pmatrix} \phi(\nu_e) \\ \phi(\nu_\mu) \\ \phi(\nu_\tau) \end{pmatrix} = \begin{pmatrix} P_{ee} & P_{e\mu} & P_{e\tau} \\ P_{\mu e} & P_{\mu\mu} & P_{\mu\tau} \\ P_{\tau e} & P_{\tau\mu} & P_{\tau\tau} \end{pmatrix} \begin{pmatrix} \phi_0(\nu_e) \\ \phi_0(\nu_\mu) \\ \phi_0(\nu_\tau) \end{pmatrix} \equiv P \begin{pmatrix} \phi_0(\nu_e) \\ \phi_0(\nu_\mu) \\ \phi_0(\nu_\tau) \end{pmatrix}, \tag{1}$$

The matrix elements P_{ij} are functions of neutrino mixing angles and CP violation phase. Since the distance between the source and earth is sufficiently large, the matrix element P_{ij} does not depend

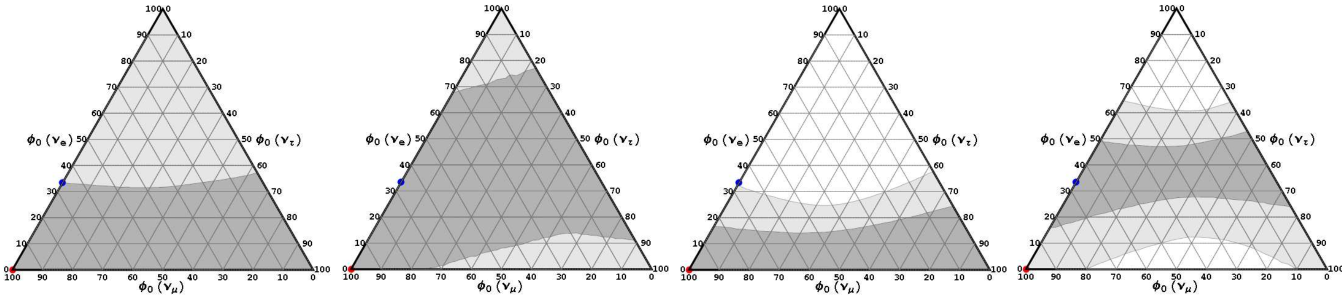

Figure 1: The reconstructed ranges of neutrino flavor ratios. The red point marks the muon-damped source $\{\phi(\nu_e) : \phi(\nu_\mu) : \phi(\nu_\tau)\}_\mu = \{0 : 1 : 0\}$, the blue one marks the pion source $\{\phi(\nu_e) : \phi(\nu_\mu) : \phi(\nu_\tau)\}_p = \{1/3 : 2/3 : 0\}$. Gray and light gray areas denote the reconstructed 1σ and 3σ ranges. The first two panels are results for an input muon-damped source and an input pion source, respectively, with only R measured ($\Delta R/R = 10\%$). The next two panels are the results for an input muon-damped source and an input pion source, respectively, with $\Delta R/R = 10\%$ and $\Delta S/S = 12\%$.

on the neutrino mass-squared differences nor depend on the neutrino energy. This study adopts the following global fitting result of neutrino mixing angles [4]

$$\sin^2\theta_{12} = 0.32^{+0.02}_{-0.02},\ \sin^2\theta_{23} = 0.45^{+0.09}_{-0.06},\ \sin^2\theta_{13} < 0.019. \tag{2}$$

The statistical analysis is performed with the following formula [5, 6]

$$\chi^2 = \left(\frac{R_{\rm th} - R_{\rm exp}}{\sigma_{R_{\rm exp}}}\right)^2 + \left(\frac{S_{\rm th} - S_{\rm exp}}{\sigma_{S_{\rm exp}}}\right)^2 + \sum_{jk=12,23,13}\left(\frac{s^2_{jk} - (s_{jk})^2_{\rm best\,fit}}{\sigma_{s^2_{jk}}}\right)^2 \tag{3}$$

with $\sigma_{\rm Rexp} = (\Delta R/R)R_{\rm exp}$, $\sigma_{\rm Sexp} = (\Delta S/S)S_{exp}$, $s^2_{ij} \equiv \sin^2\theta_{ij}$ and $\sigma_{s^2_{jk}}$ denote the 1σ range of s^2_{ij}. The suffix "th" indicates the theoretical predicted value which depends on the source neutrino flavor ratio and the neutrino mixing angles in Eq. (2). The suffix "exp" indicates the experimentally measured value which is generated by the true neutrino flavor ratio and the best-fit values of neutrino mixing angles. ΔR and ΔS are assumed to be dominated by statistical errors which imply [5]

$$\left(\frac{\Delta S}{S}\right) = \frac{1+S}{\sqrt{S}}\sqrt{\frac{R}{1+R}}\left(\frac{\Delta R}{R}\right), \tag{4}$$

It is easier to measure R than to measure S. We present results of neutrino flavor reconstruction in Fig. 1. The reconstructed region of neutrino flavor ratio with $\Delta R/R = 10\%$ and $\Delta S/S = 12\%$ (Poisson relation) is much smaller than the reconstructed region with the measurement $\Delta R/R = 10\%$ only. For an input muon-damped source, the pion source can be ruled out at the 3σ level with both R and S measured to the above mentioned accuracies. On the other hand, for an input pion source, the muon-damped source can not be ruled out at the 3σ level under the same condition. The ranges for neutrino mixing angles and the true value for the CP phase could affect the reconstructed range for the neutrino flavor ratio. These effects are shown in Fig. 2.

3 Conclusion

We have illustrated the reconstruction of the neutrino flavor ratio at the source from the measurements of energy-independent ratios $R \equiv \phi(\nu_\mu)/(\phi(\nu_e) + \phi(\nu_\tau))$ and $S \equiv \phi(\nu_e)/\phi(\nu_\tau)$ among integrated neutrino flux. By just measuring R alone from either an input pion source or an input muon-damped source

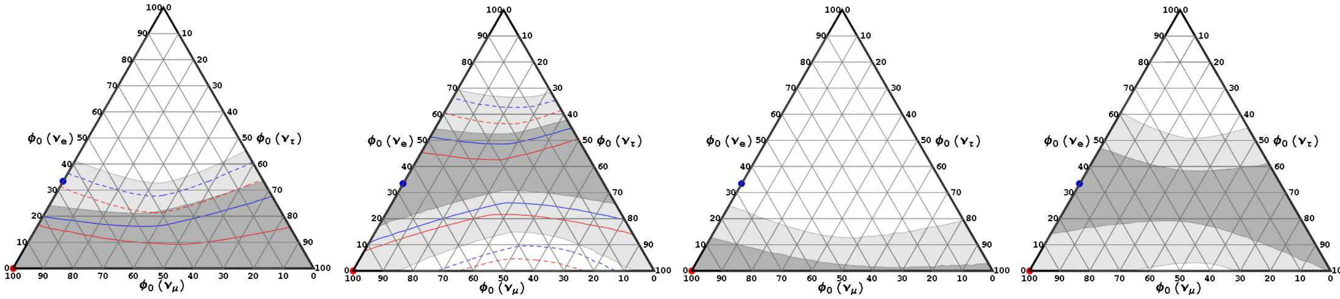

Figure 2: The reconstructed range of neutrino flavor ratio with different values of neutrino mixing angles. The first two panels are obtained with $\sin^2\theta_{13} = 0.016 \pm 0.010$ [7], and the input CP phase taken to be 0, $\pi/2$ and π respectively. The ranges for θ_{12} and θ_{23} follow Eq. (2). Light gray area, dashed blue and dashed red lines correspond to 3σ ranges for the reconstructed neutrino flavor ratio at the source for $\cos\delta = 1$, $\cos\delta = 0$ and $\cos\delta = -1$ respectively. Gray area, blue and red lines correspond to 1σ ranges for the reconstructed neutrino flavor ratio at the source for $\cos\delta = 1$, $\cos\delta = 0$ and $\cos\delta = -1$ respectively. The next two panels are the results for an input muon-damped source and an input pion source, respectively, with $\sin^2\theta_{23} = 0.55^{+0.09}_{-0.06}$. The ranges for θ_{12} and θ_{13} follow Eq. (2). All of the panels are obtained with $\Delta R/R = 10\%$ and $\Delta S/S = 12\%$.

with a precision $\Delta R/R = 10\%$, the reconstructed 3σ range for the initial neutrino flavor ratio covers the entire physical range for the above ratio. By measuring both R and S from an input muon-damped source, the pion source can be ruled out at the 3σ level with $\Delta R/R = 10\%$ and $\Delta S/S$ related to the former by the Poisson statistics. The full details of our studies are presented in [8].

Acknowledgements The authors appreciate supports by National Science Council, Taiwan, under the Grant No. 96-2112-M-009-023-MY3, Research and Development Office, National Chiao-Tung University and Leung Center for Cosmology and Particle Astrophysics, National Taiwan University.

References

[1] J.P. Rachen and P. Meszaros, *Phys. Rev.* D 58 (1998) 123005

[2] T. Kashti and E. Waxman, *Phys. Rev. Lett.* 59 (2005) 181101

[3] M. Kachelriess, S. Ostapchenko and R. Tomas, *Phys. Rev.* D 77 (2008) 023007

[4] M.C Ganzales-Garcia and M. Maltoni, *Phys. Rep.* 460 (2008) 1

[5] K. Blum, Y. Nir and E. Waxman, arXiv:0706.2070 [hep-ph]

[6] S. Choubey, V. Niro and W. Rodejohann, *Phys. Rev.* D 77 (2008) 11306

[7] G.L. Fogli, E. Lisi, A. Marrone, A. Palazzo and A.M. Rotunno, *Phys. Rev. Lett.* 101 (2008) 141801

[8] K. C. Lai, G. L. Lin and T. C. Liu, *Phys. Rev.* D 80 (2009) 103005